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Abstract: Process- and chemical plants may constitute a critical target for a terrorist attack. In the present study, the analysis of industrial accidents induced by intentional acts of interference is carried out focusing on accident chains triggered by attacks with home-made (improvised) explosives. The effects of blast waves caused by improvised explosive devices are compared with those expected from a net equivalent charge of TNT by using a specific methodology for the assessment of stand-off distances. It is demonstrated that a home-made explosive device has a TNT efficiency comprised between 0.2 and 0.5. The model was applied to a case study, demonstrating the potentiality of improvised explosives in causing accident escalation sequences and severe effects on population and assets. The analysis of the case-study also allowed obtaining suggestions for an adequate security management.

***Cover Letter**

CONSIGLIO NAZIONALE DELLE RICERCHE

ISTITUTO DI RICERCHE SULLA COMBUSTIONE

November 3rd, 2014

To the kind attention of the

Editors of the Special Issue on Domino Effects

Reliability Engineering and System Safety

Object: **Manuscript Submission**

Dear Editors,

Please receive the paper "*Vulnerability of Industrial Facilities to Attacks with Improvised Explosives Devices aimed at Triggering Domino Scenarios*" by Gabriele Landucci, Genserik Reniers, Valerio Cozzani, Ernesto Salzano.

The paper has been submitted for the special issue on Domino Effects of the Elsevier's journal "Reliability Engineering and System Safety", and deals with the domino effects, and more in general, industrial risks related to improvised or home-made explosives.

Sincerely yours,

Dott. Ernesto Salzano

Vulnerability of Industrial Facilities to Attacks with Improvised Explosives Devices aimed at Triggering Domino Scenarios

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ABSTRACT

Process- and chemical plants may constitute a critical target for a terrorist attack. In the present study, the analysis of industrial accidents induced by intentional acts of interference is carried out focusing on accident chains triggered by attacks with home-made (improvised) explosives. The effects of blast waves caused by improvised explosive devices are compared with those expected from a net equivalent charge of TNT by using a specific methodology for the assessment of stand-off distances. It is demonstrated that a home-made explosive device has a TNT efficiency comprised between 0.2 and 0.5. The model was applied to a case study, demonstrating the potentiality of improvised explosives in causing accident escalation sequences and severe effects on population and assets. The analysis of the case-study also allowed obtaining suggestions for an adequate security management.

Keywords

Improvised explosives; ANFO; TATP; domino effect; overpressure; security management

Highlights

- Improvised explosives possibly used for terrorist attacks were described
- The TNT efficiency of ANFO and TATP was characterized
- Domino effects caused by an attack with improvised explosive were analyzed
- Domino scenarios induced by an attack were compared to conventional scenarios

1. Introduction
Industrial facilities where relevant quantities of hazardous chemicals are stored or processed may be possible targets for malicious acts of interference due to terrorist attacks. The credibility and potential severity of such scenarios was pointed out by several previous studies devoted to the evaluation of the potential impact of external attacks on process plants [1–9]. An important aspect associated to such integrated safety and security analysis is that accidents triggered by external attacks may damage multiple process units or eventually several neighboring industrial sites triggering domino effects [9–11].
According to the schematization reported in Figure 1, the attack may take place inside the industrial domain, hence aiming at the direct damage of target equipment by bombs or firearms, and to trigger an escalation sequence leading to a domino scenario (also defined as a "cascading event") [12–19]. Otherwise, an intentional act of interference still having the plant as the main target may as well be initiated outside the plant boundaries [14,20–22]. Moreover, intentional attacks to non-industrial targets (e.g. strategic buildings, urban areas, infrastructures) might produce a large-scale accident which may in turn trigger indirect external domino effects in an industrial facility. Domino scenarios triggered by such attacks are likely to have an extremely high severity [12–19], as remarked in Figure 1. This highlights the importance of an appropriate security management of chemical and process facilities which should ideally be integrated with the analysis of the area surrounding the facility itself.

[INSERT FIGURE 1 HERE]

The fundamental basis of security management can be expressed in a similar manner to the Layers of Protection used in modern chemical process plants for addressing safety-related, accidental events. In the security-related concept of concentric "Rings-of-Protection" [23,24], also known as 'layered defenses', the spatial relationship between the location of the target, the location of the physical countermeasures and the location of adversary, may be used as a first guiding principle. Besides, an effective countermeasure deploys multiple defense mechanisms between the adversary and the target asset. Each of these mechanisms should present an independent obstacle to the adversary, as schematized in Figure 1. These concepts are directly applicable to contrast the effects produced by home-made (improvised) explosives in a non-military context. However, in this paper deliberate attacks on industrial plant are considered [25]. In this case, (i) the resistance of the barriers, (ii) the time it takes an adversary to get to the target, and (iii) the distance an adversary might take to place a home-made explosive are the most important factors to take into account to assess the probability of success and to minimize the damage. However, the design of the three cited countermeasures (resistance, time, distance) is not straightforward and depends on several deterministic variables.
The present study investigates the possibility that a shock wave generated by home-made (or improvised) explosives may damage process equipment and/or trigger an escalation sequence resulting in a domino scenario. The analysis was mainly based on the assessment of stand-off distances between the explosion source and the target (the industrial plant) as principal countermeasure, but the barrier resistance was also addressed. Specific curves were defined in order to determine the peak overpressure on the basis of the explosive type and amount. A case study is also analyzed in order to evaluate the vulnerability of process plants to attacks based on improvised explosives. The case study also compares the impact of the worst-case accidents triggered by external attack with domino chains induced by internal process failures.

2. Home-made explosives
According to the US Government Hazardous Substances Database, several substances and mixtures can be used for the realization of this kind of explosives, starting from chemicals sold in markets and pharmacies. Among others, two were often adopted for terrorist attacks, suicide bombing, and

other malicious uses: Ammonium Nitrate (AN) - Fuel Oil (i.e. ANFO) mixtures and Acetone Peroxide or Triacetone Triperoxide Peroxyacetone (TATP) mixtures [26–28]. These two materials were considered as reference explosives for the analysis presented in the present study.

ANFO is a tertiary explosive (note that TNT is a secondary explosive) and is generally composed by 94% of AN prills and 6% of adsorbed fuel oil [29]. It is extensively used for several authorized purposes as in mine blasting. The TNT equivalence is typically around 80% and the ideal explosion (detonation) energy is 3890 kJ/kg (pure ammonium nitrate has an explosion energy of 1592 kJ/kg). AN prills used for mining applications are however physically different from fertilizer prills used in home-made explosives. The commercial ammonium nitrate prills used for mine blasting have a 20% void fractions and are coated with #2 fuel oil (mainly C10 to C20 linear hydrocarbons) or kerosene. Hence, ANFO has a bulk density of approximately 840 kg/m^3 when starting from AN prills for mining applications, having a density of about 1300 kg/m^3 (the density of pure crystalline ammonium nitrate is 1700 kg/m^3). On the other hand, homemade explosives prepared from AN fertilizers do not have a so high void fraction and are less efficient: e.g. the new European regulations for fertilizers [30] state that they must contain less than 45% of AN (16% N) for being traded to the general public. Such fertilizers still may be used to obtain explosives, but require processing to achieve a detonation. If commercial AN (containing about 50% of inert, as dolomite) and diesel fuel is used, a detonation energy of about 1071 kJ/kg is obtained, much less than pure ANFO [27]. Furthermore, it has been observed that when amounts of dolomite higher than 30%, are present, no detonation is observed [27].

TATP is a primary explosive which is notable since it does not contain nitrogen. Thus, it is used to avoid conventional chemical bomb detection systems, and it is almost undetectable by either analytical system or by sniffer dogs [31]. It can be obtained from common household items such as sulphuric acid, hydrogen peroxide, and acetone [32].

TATP is very unstable: it can be ignited by touch and can explode spontaneously. It is often used for detonators. It is actually composed by isomers and conformers, the dimer being more stable but having lower decomposition energy (see Figure 2).

[INSERT FIGURE 2 HERE]

The density of the pure molecule is typically considered to be 1220 kg/m^3. However, home-made TAPT formulations are typically in the range of 450-500 kg/m^3 [33]. Finally, TATP is often stabilized with carbonaceous liquids and waxes so that the net charge is even lower [34]. Nevertheless, Lefebvre et al. [35] have demonstrated that home-made TATP is a primary explosive and very sensitive to impact or friction, although the strength of explosion may strongly vary since the quality of the final product is very sensitive to the temperature during its synthesis.

TATP is highly volatile and decomposes to form large number of gas phase molecules (entropic explosion) [36,37]. Acetone and ozone are predicted to be the main decomposition products, along with oxygen, methyl acetate, ethane, and carbon dioxide [38].

3. Methodology

3.1 Assessment of explosion effects for improvised explosives

The aim of the study is to support consequence and vulnerability assessments of industrial plants (hence equipment) when subject to a shock wave produced by improvised explosive devices based on ANFO or TATP. To this aim, the calculation of the pressure history (maximum pressure, positive duration, impulse) with respect to the distance from the explosion point is needed. In order to obtain this information, the amount of explosive and its efficiency with respect to an equivalent amount of TNT (W_{TNT}) is required. The Hopkinson-Cranz methodology to calculate the mass-scaled distance (Z) is typically adopted for point-source explosives [39]:

$$W_{TNT} \times \Delta H_{TNT} = \kappa \times W_{exp} \times \Delta H_{exp} \quad (1)$$

$$Z = r / W_{TNT}^{1/3} \quad (2)$$

where W_{exp} is the mass of the generic explosive, ΔH_{TNT} is the TNT explosion energy, which is typically 4.6 MJ/kg, ΔH_{exp} is the explosion energy of the material of interest, related to the primary explosion only (decomposition or detonation energy) and not to the overall combustion energy, and κ is a coefficient which depends on the confinement or, more specifically, to the mechanical energy adsorbed for the deformation and failure of the containment system [40]. For explosives contained in low-strength enclosure, a factor κ = 0.7 could be adopted, however we used unitary values in order to obtain safe-side evaluations. The parameter r represents the actual distance from the center of the explosion.

Quite clearly, two pieces of information are needed to determine W_{TNT}: (i) the mass W_{exp} and (ii) the ratio of explosion energy of the material of interest with respect to that of TNT, which is called the TNT efficiency (η).

Several previous publications [26,41,42] provide data, references and correlations for the shock wave produced by ANFO and TATP. What is relevant for the present study is that: (i) the explosion energy gives a good reproduction of the destructive power of the substances at constant, atmospheric pressure (which is the case hereby analyzed); (ii) light confinement (even a paper confinement) approximately doubles the severity of the explosion; (iii) high-strength confinement as the steel case adopted for bombs and military explosive devices has been not considered, hence the corresponding effects of casing fragmentation have been neglected; and (iv) the energy output from non-ideal explosives is dependent on charge size, which makes it difficult to define it with traditional modeling methods. However, since the energy output decreases with the charge size [26,41,42], we neglected the variation of TNT efficiency adopting the correspondent maximum value in order to obtain conservative estimations.

Table 1 reports the TNT efficiency (η) obtained from specific studies [26,41,42] and calculated as the ratio between the explosion energy of the mixture of interest and the explosion energy of TNT (namely, detonation energy ratio) for different types of explosives. In the case of non-ideal mixtures, the property values have been calculated by using the Chemical Equilibrium Model (CEA) as previously done in the literature for black powder [43] and pyrotechnics [44]. Quite clearly, discrepancies can be found with respect of the reaction heats given in the open literature. However, the figures obtained by the CEA model are at least indicative of the explosion energies involved.

[INSERT TABLE 1 HERE]

Table 1 reports data for home-made explosives produced with 90% and 50% non-porous AN in mass with dolomite as inert material mixed with fuel oil (respectively “AN/dolomite (90/10) + diesel fuel” and “AN/dolomite (50/50) + diesel fuel”). It is worth noticing that the efficiency of pure ANFO is consistently larger than that of possible home-made explosives based on fertilizers, in which some inert material as dolomite is used, and diesel fuel and non-porous AN as explosive component are employed. Reduction to very low values of TNT efficiencies can clearly be observed.

Finally, it is well known that η refers to the shock wave produced in unconfined explosion, which is only related to the primary explosion. Besides, the heat of combustion, which is much larger with respect to the explosion energy, should be considered for quasi-static analysis if confinement is taken into account [45].

On the basis of the above assessed TNT efficiency values, the peak overpressure may be estimated by adapting the following literature correlation [46]:

$$P_s = \frac{W_{TNT}^{1/3}}{r} + 4.4\frac{W_{TNT}^{2/3}}{r^2} + 14.0\frac{W_{TNT}}{r^3} \quad (3)$$

where P_s (bar) is the peak overpressure, r (m) is the distance from the center of the explosion and W_{TNT} is the equivalent mass of TNT expressed in kg, calculated accordingly to the following expression for a given amount of home-made explosive (W_{exp} expressed in kg):

$$W_{TNT} = \eta \times f \times W_{exp} \quad (4)$$

where W_{exp} is the overall amount of home-made explosive considered, η is the TNT efficiency, and f is the actual mass fraction of the explosive material, introduced, in order to consider the possible presence of inert materials in home made explosives.

Combining Eq.s (3) and (4), modified TNT diagrams were be obtained for each of the explosive material obtained. The modified diagrams, shown in Figure 4, allow the straightforward assessment of overpressure as a function of distance, of explosive type and of explosive amount [47,48].

3.2 Assessment of damage to equipment

Since the main aim of the present study is determining the damage and impact of blast waves caused by improvised explosive devices on process equipment, vulnerability models need to be introduced to assess potential damages and to verify the possibility of escalation triggering a domino chain leading to further damage caused by fires [49], explosions [50] and fragment projection [51,52]. Vulnerability of process equipment to blast waves depends on the pressure history, and large difficulties arise if a deterministic analysis is required. Hence, for the aim of the present study, existing dose-effects analysis based on peak overpressure will be adopted, assuming conservatively a static interaction [53–56]. In the static analysis, hence neglecting the dynamic contribution, the escalation threshold for the explosion resilience depends on the equipment construction and operation characteristics, and is expressed as the peak overpressure value at the position of the target equipment. A procedure and specific threshold data for equipment damage assessment due to blast waves are detailed in previous studies [53–57]. The quality of available data only allows defining broad categories of equipment [57]. Table 2 summarizes the categories of equipment considered and the corresponding overpressure threshold values for damage and escalation.

[INSERT TABLE 2 HERE]

3.3 Case study definition

The analysis of an industrial facility surrounded by residential areas is taken into account in order to apply the results of the present work. An overview of the area where the facility is located is shown in Figure 3a, while the layout considered for the case study is reported in Figure 3b. Several tanks storing hazardous materials are located in the storage areas of the plant, as shown in detail in Figure 3b. The main features of the tanks are reported in Table 3.

[INSERT FIGURE 3 HERE]

[INSERT TABLE 3 HERE]

A consequence analysis based on a vulnerability assessment was performed in order to show the different potential impacts of domino scenarios triggered by internal process failures with respect to escalation scenarios generated by external acts of interference carried out by means of home-made explosive devices. In particular, the following cases were considered:

- Scenario (1): only primary scenarios occur (i.e., primary scenarios associated to each tank without considering the possibility of domino effect);
- Scenario (2): occurrence of domino effect triggered by internal process failures (i.e. primary fire impacting on nearby process equipment);
- Scenario (3): “severe” external terrorist attack with a high amount of home-made explosive (50000 kg of AN/dolomite 50/50) in position P1, outside the industrial facility (see Figure 3b);
- Scenario (4): same as case 3 but considering attack in position P2 (see Figure 3b);
- Scenario (5): “weak” external terrorist attack with limited quantities of explosive (50 kg of TATP) at position P3 inside the industrial facility (see Figure 3b);

Table 4 summarizes the primary and secondary scenarios identified for each of the vessels considered in the lay-out.

[INSERT TABLE 4 HERE]

It is worth to notice that on one hand the home-made explosive selected for the “severe” external attacks (i.e. for scenarios 3 and 4) may be rather easily produced in large amounts and positioned outside the plant, e.g. by parking one or more trucks on the road close to the plant fences (see Figure 3b). On the other hand, when an attack using explosives inside the plant (i.e. scenario 5) is considered, the use of such amounts of explosives is not credible due to the difficulties in introducing them in an industrial facility, even without that specific security measures are taken. Since limited amounts of AN-based explosive are not able to cause relevant damages to process equipment from distances greater than 10m (see Section 4.1), TATP is instead considered, assuming that 50kg of explosive may be carried inside a facility up to a maximum distance of 20m from the storage area (see e.g. position P3 in Figure 3b).
In the case of domino effect caused by internal process malfunctions (scenario 2), the pool-fire following the rupture of tank AT8 is the primary scenario triggering domino escalation. In order to determine the possible escalation targets, the threshold values for thermal radiation reported in Table 2 were considered, following the procedure for domino target identification discussed by [57].
The impact of the explosions is assessed through the use of the present methodology, whereas integral models for radiation heat effects are used for the analysis of fire scenarios. Uniform wind direction, 5 m/s wind speed and stability class D were assumed for consequence assessment.
In order to obtain a homogenous representation of the consequences, a vulnerability assessment was carried out. For each accident scenario, the contour of 1% lethality was calculated applying probit equations available in the literature [58,59] and summarized in Table 5 . Each contour identifies the area inside which the probability of death is higher than 1%.

[INSERT TABLE 5 HERE]

4. Results and Discussion

4.1 Impact distances of improvised explosives

The methodology adopted for the impact assessment of the improvised explosives allows obtaining the impact charts shown in Figure 4. In each chart, the peak overpressure is reported as a function of the distance given the explosive quantity (in kg), according to Eq. (3).

[INSERT FIGURE 4 HERE]

Figure 4a shows the data obtained for TATP. Large amounts of this explosive are too hazardous to produce, transport, and manipulate. Indeed, TATP is typically an explosive adopted for single-man suicide attacks [32,38]. A net-charge of 50 kg can be transported e.g. in backpack, while higher quantities are deemed not to be credible in a terrorist attack as highlighted in Figure 4a due to both stability and transportation problems. Therefore, the impact associated to TATP explosions may be significant only close to the target equipment and it may be prevented adequately managing the physical and operational security and the access to the industrial site.
Conversely, self-produced AN explosives may be obtained in extremely large quantities, e.g. from several kilograms up to quantities as high as e.g. 50 tons. In the latter case, the explosive can be positioned outside the restricted industrial area, loaded in a car or even in a truck parked on the road adjacent to the fence of the industrial facility. This is confirmed by the results in Figure 4b, that show the impact chart for AN/dolomite (50/50) with diesel fuel mixture (see Table 1). Even if the efficiency and the explosive fraction (e.g. 50%) are limited, extremely high amounts of this type of explosive may have a significant impact on equipment and structures even from distances of few hundred meters.
The methodology defined may also be used to provide data for other improvised explosives. Eq.(4) may be applied in order to estimate the equivalent amount of TNT (W_{TNT}), and the chart reported in Figure 4c may thus be used to estimate the impact distance.
In order to determine the potential impact of a terrorist attack carried out with home-made explosives against process equipment, “stand-off distances” were evaluated. In the present study, the stand-off distance is defined as the minimum distance between the asset of interest and the area where an explosive device can be placed without causing damages [42].
Figure 5 shows the calculated stand-off distances for several types of industrial equipment reported as a function of the net explosive mass in the home-made explosive charge. Figure 5 was obtained applying Eqs. (3) and (4), and considering the threshold values for domino effects (Table 2).

[INSERT FIGURE 5 HERE]

Figure 5a shows the results obtained for atmospheric equipment. Figures 5b and 5c the results for different categories of pressurized equipment. Pure ANFO and TATP exhibit similar results, due to the similar efficiency and to the absence of inert material. However, the presence of dolomite and the lower efficiency deplete AN improvised explosives. As shown in Figure 5, the stand-off distance for this type of explosive is about half of that calculated for the correspondent pure explosive.

4.2 Results of the case study

Figure 6 reports the results obtained for the analysis of the primary events associated to the tanks in the facility (scenario 1).

[INSERT FIGURE 6 HERE]

Figure 6a shows the contour of 1% lethality for the primary scenarios summarized in Table 4. It is worth to notice that some curves extend outside the fences of the facility, but none of the scenarios is able to impact on the residential areas located close to the East and North boundaries of the plant (see Figure 3a).
Figure 6b shows in detail the iso-radiation contours obtained for the pool fire in AT8 catch basin in order to support the assessment of escalation given by internal process failures. As shown in the figure, several tanks are exposed to severe heat radiation, with potential escalation triggered by fire

leading to domino scenarios. In particular, Table 4 summarizes the secondary scenarios associated to the equipment items for which the pool fire radiation is higher or equal to the correspondent threshold value, reported in Table 2.
For what concerns the assessment of the scenarios triggered by overpressure, the stand-off distance charts reported in Figure 5 are used in order to identify the possible targets that may lead to the escalation if damaged. In particular, Figure 5a was used for the atmospheric tanks, Figure 5b for the pressurized sphere S1.
Figure 7 shows the results obtained for the different types of domino scenarios, both triggered by process internal failures or from external attack.

[INSERT FIGURE 7 HERE]

Depending on the attack position, the impact of the resulting domino scenarios is extremely different even if the attack is carried out with large amounts of explosives. In particular, in the case of a "severe" attack outside the plant in position P2 (scenario 4), the explosion has the potential to affect only the atmospheric tanks located on the East side of the plant, thus triggering secondary pool fires that are not able to affect the residential area. The red circles in Figure 7c, representing the 1% lethality curve associated to the secondary events triggered by the explosion, are in fact still inside the plant boundaries. On the contrary, the explosion itself has a strong impact on the population, as demonstrated in Figure 7c by the blue circle, representing the vulnerability contour associated only to the explosion. If the location of the attack is changed from P2 to P1 keeping the same potentiality (scenario 3), the explosion is strong enough to affect the sphere S1, storing pressurized liquefied propane. The catastrophic failure of the sphere leads to a fireball, an extremely severe scenario which effects are represented in Figure 7b. As shown in the figure, the contour associated to the explosion (blue circle in Figure 7b) is included in the area affected by the secondary event (red circle in Figure 7b). Hence, this demonstrates the sensitivity associated to the position of the attack.
The same type of results is obtained in the case of a "weak" attack (scenario 5), in which the home-made explosive is not able to generate severe damages to the population but it has the potential to damage the equipment inside the storage facility. Figure 7d shows the results obtained for case 5: the TATP explosion is able to affect the pressurized sphere S1, leading to the fireball with the same effects found for case 3, even if the quantity of explosive used in this case is three orders of magnitude lower in weight. However, considering the TNT equivalent quantity, the amount of TATP is about 200 times lower with respect to the ANFO explosive device adopted in case 3.
Finally, in the case of domino effects triggered by internal failures (scenario 1, Figure 3a) the fireball is still the most final event, but with a higher impact with respect to the previous cases. Indeed, in this case, the rupture occurs after the liquid has reached a higher pressure and temperature, thus having a higher energy potential before the rupture [60,61]. The escalation scenario has significant effects inside the facility. A higher severity is thus associated to escalation caused by internal process failures.

4.3 Discussion

The case study illustrated in the previous section has demonstrated the importance of security risk assessment in the chemical and process industry. As a matter of fact, a systematic approach is needed in order to organize information concerning the assets that need to be protected, the threats that may be posed against those assets, and the likelihood and consequences of attacks against them. In this framework, the list of the 'attractive' installations and storage tanks must include also company installations that may be a target for adversaries aiming at inducing domino effects. Furthermore, the possible nearby roads and access roads from where an adversary may carry out a

domino effect inducing attack with home-made explosives, should be determined, depending on the proximity of the installations and storage areas to the fences at the border of the plant.
The security hazard and risk identification process should identify all company security risks, including – and especially – domino effect risks. More information on security hazard identification in a chemical industrial surrounding are reported in the literature [25]. Typically, it is the responsibility of the security manager, together with the organization's board, to conclude whether the risk is acceptable, tolerable (ultimately with countermeasures), or unacceptable, hence to be mitigated. Every step in the process has to be rigorous and transparent so that changes over time can be captured as well.
Based on the results obtained in our case study, it is important to design rings of protection in a way that escalation effects leading to domino scenarios are taken into account. Every ring is defined and constructed according to the risk sensitivity of the objects inside a zone (e.g. storage of flammable liquids; a reactor that is prone to explode during process disturbances, etc.). The barriers that protect a specific ring are designed with a certain 'resistance against intrusion'. The target in the center is the asset that is deemed 'attractive' for a potential adversary and therefore requires protection. However, as already mentioned, our case study reveals that if an escalation effect can be induced from a nearby installation onto an 'attractive' installation, it may be important to protect this nearby installation as adequately as the 'more attractive' installation, and include it into the zone of protection of this installation.
Security management within a chemical plant should be aware of this. On the one hand, the resistance of a barrier and the time it takes an adversary to get to the target, are important factors in the likelihood of interruption when setting up an analysis of the path an adversary might take to place a home-made explosive device. On the other hand, suicide bombers, who are only interested in forced entry, should be considered as well. Hence, it is obvious that a diversity of security countermeasures is needed in a chemical company.
Security management by means of the rings-of-protection concept [23,24], translates into a number of measures, as it is a combination of physical security equipment, people and procedures. Elements of all these types are typically needed together in order to offer the best chance of adequate asset protection against a variety of threats, amongst others improvised explosives used to trigger an escalation sequence leading to a domino scenario.

5. Conclusions

In the present study, the potentiality of home-made improvised explosives to trigger domino scenarios was investigated. A preliminary characterization of improvised explosives was carried out determining the explosion potential and stand-off distances.
The classical TNT-energy or mass-scaled analysis has been proved to give sufficiently accurate results with CHN-based high-energy explosives similar to TNT. However, further work should be devoed for non ideal substances with lower explosion energies, or for the behavior of an explosive material when density, composition, humidity and other chemical and physical parameters affects their efficiency.
A case study allowed comparing the escalation hazard due to improvised explosive devices with that associated to accidents caused by internal process failures.
The results obtained showed that domino effects caused by terrorist attacks with home-made explosives can be triggered only if the explosives are positioned inside the facility or at least very near to process equipment or storages. Hence, adequate industrial site security measures may effectively prevent this event.
On the other side, external attacks outside the plant, even in presence of huge amounts of explosive, might be able to trigger severe escalation scenarios only in case of proximity to critical 'attractive' equipment, while in other cases relevant consequences are only associated to direct damage to the population.

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TABLES

Table 1: Experimental heat of explosion (ΔH_{exp}) and combustion (ΔH_{comb}) and TNT efficiencies (η) for the analyzed explosives. AN: ammonium nitrate; FO: fuel oil; DF: diesel fuel.

Explosive	**ΔH$_{exp}$ (kJ/kg)**	**ΔH$_{comb}$ (kJ/kg)**	**η (-)**	
			Literature data	**Calculated[a]**
TNT	4680	14961	1.00	1.00
ANFO (94% AN; 6% FO)	3890	578	0.60 – 0.88	0.83
TATP (Trimer)	2803	28192	0.30 – 0.92[b]	0.60
DADP (Dimer)	-	23465	-	1.26
AN/dolomite (90/10) + DF	3234	-	-	0.69
AN/dolomite (50/50) + DF	1071	-	-	0.23

[a] Ratio between the explosion energy of the mixture of interest and the explosion energy of TNT (namely, detonation energy ratio)

[b] Mixture of isomers

Table 2: Escalation thresholds for the escalation due overpressure and heat radiation for different equipment categories [57].

Equipment category	**Overpressure (bar)**	**Heat radiation (kW/m^2)**
Atmospheric vessels	0.22	15
Pressurized vessels	0.20	45
Pressurized elongated vessels (toxic materials)	0.20	45
Pressurized elongated vessels (flammable materials)	0.31	45

Table 3: Main features of the storage vessels considered in the case-study. Vessel position and plant lay-out is shown in Figure 3b.

Vessel ID	**Vessel type**	**Diameter (m)**	**Height (m)**	**Stored substance**	**Inventory (ton)**	**Operating pressure (barg)**
AT1-AT4	Atmospheric	12	14.4	Ethanol	900	0.1
AT5-AT8	Atmospheric	18	9	Benzene	1500	0.1
AT9-AT18	Atmospheric	21	9	Petroleum products	1700	0.1
S1	Pressurized	12	-	Propane	300	8.5

Table 4: Primary event and secondary scenarios (escalation domino effect) for the equipment considered in the case-study. Vessel type and other relevant details are reported in Table 3 (see the corresponding vessel ID). Details on attack position are reported in Figure 3. NE = No Escalation.

Vessel ID	**Primary event**	**Secondary scenario (process causes)**	**Secondary scenario (attack P1)**	**Secondary scenario (attack P2)**	**Secondary scenario (attack P3)**
AT1	Pool fire[a]	NE	Pool fire[a]	NE	NE
AT2	Pool fire[a]	NE	NE	NE	NE
AT3	Pool fire[a]	NE	Pool fire[a]	NE	NE
AT4	Pool fire[a]	Pool fire[a]	NE	NE	NE
AT5-AT7	Pool fire[a]	Pool fire[a]	Pool fire[a]	NE	NE
AT8	Pool fire[a]	-[b]	Pool fire[a]	NE	NE
AT9-AT18	Pool fire[a]	NE	NE	Pool fire[c]	NE
S1	Jet-fire (1” hole)	Fireball	Fireball	NE	Fireball

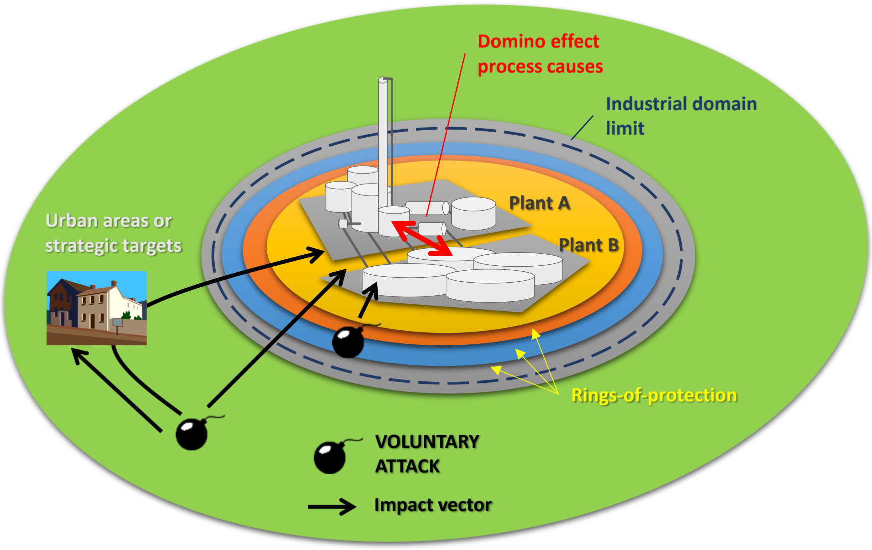
[a] Bund is present (A= 1200 m^2; H = 1.5 m).
[b] The rupture of this tank leads to domino effect escalation triggered by process causes.
[c] Bund is present (A= 1400 m^2; H = 1.5 m).

Table 5: Probit equations used for vulnerability assessment [58,59].

Physical effect	Probit equation	Notes
Radiation	$Y = -14.9 + 2.56 \ln(t_e \times I^{4/3} \times 10^{-4})$	t_e [s] : exposure time[a]; I [kW/m^2]: radiation
Overpressure	$Y = -15.6 + 1.93 \ln(P_s)$	P_s [Pa]: peak overpressure

[a] t_e is assumed 300s for pool or jet fire, while for fireball t_e is equal to the fireball duration.

FIGURES



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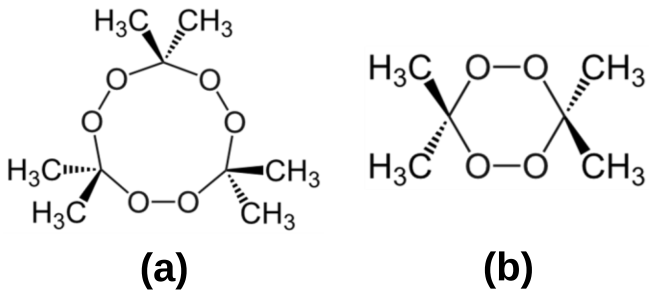

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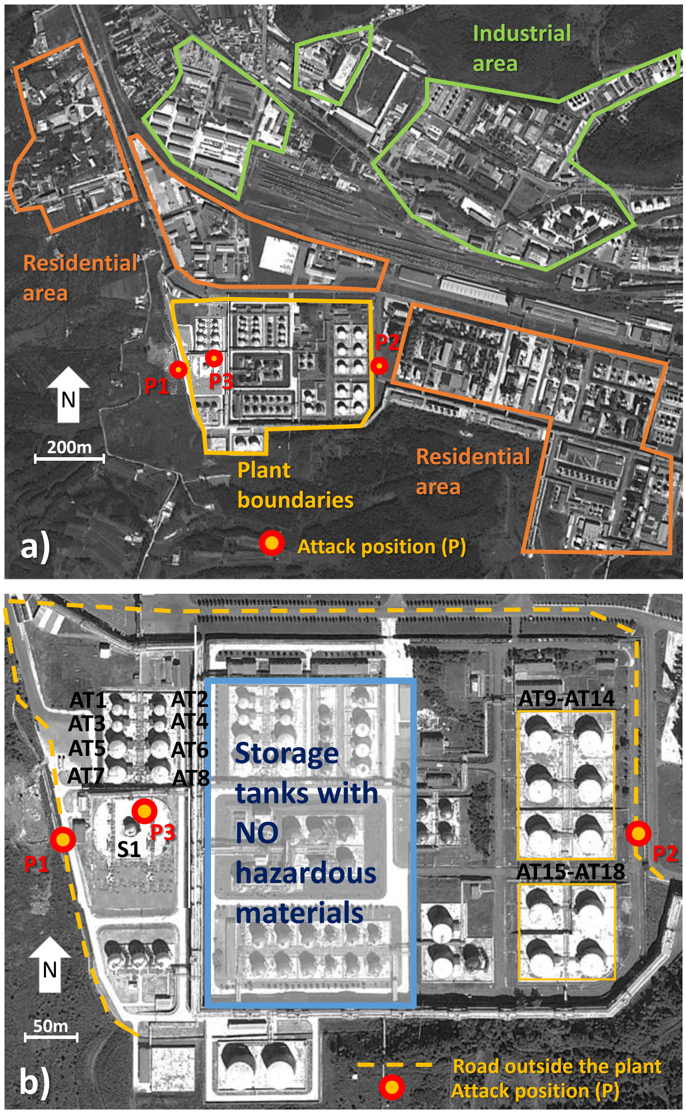

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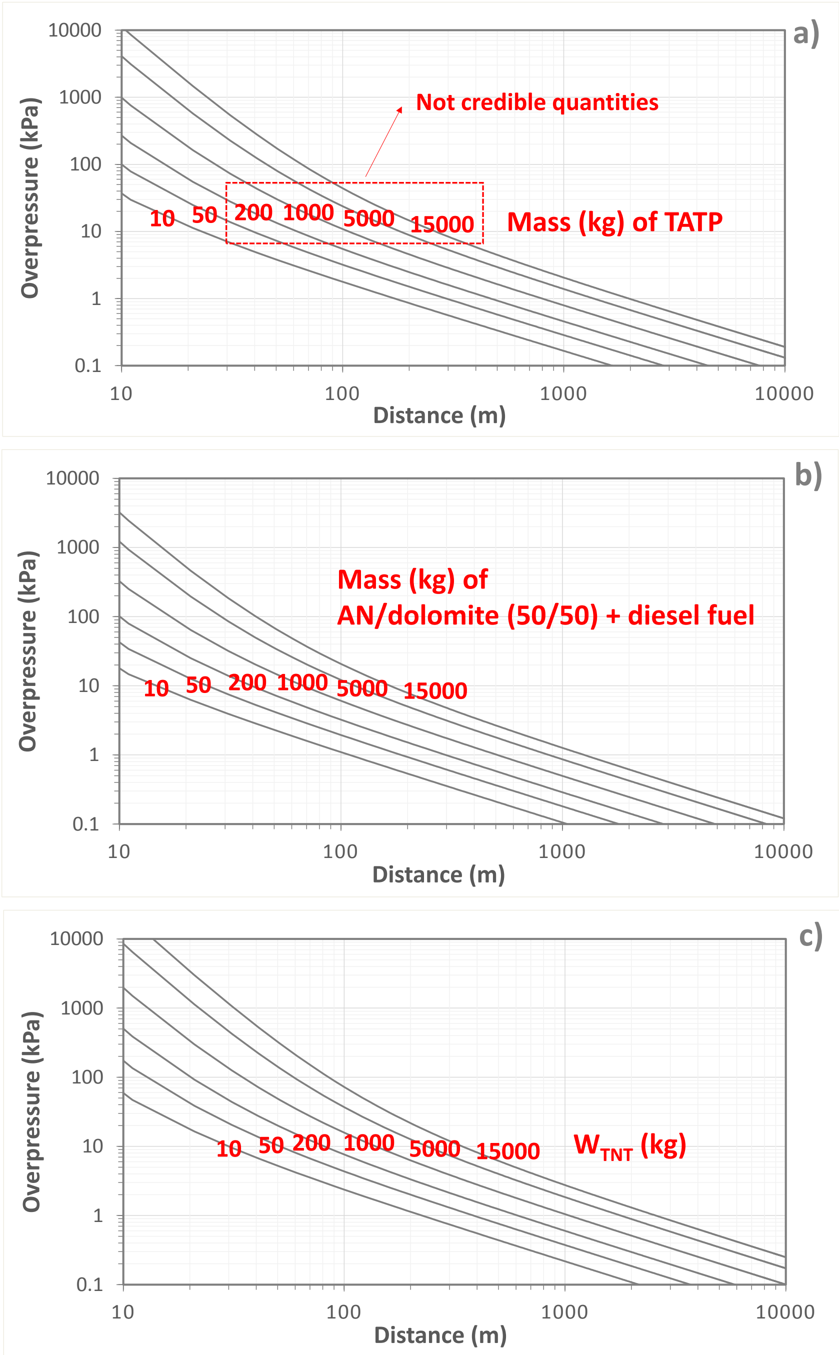

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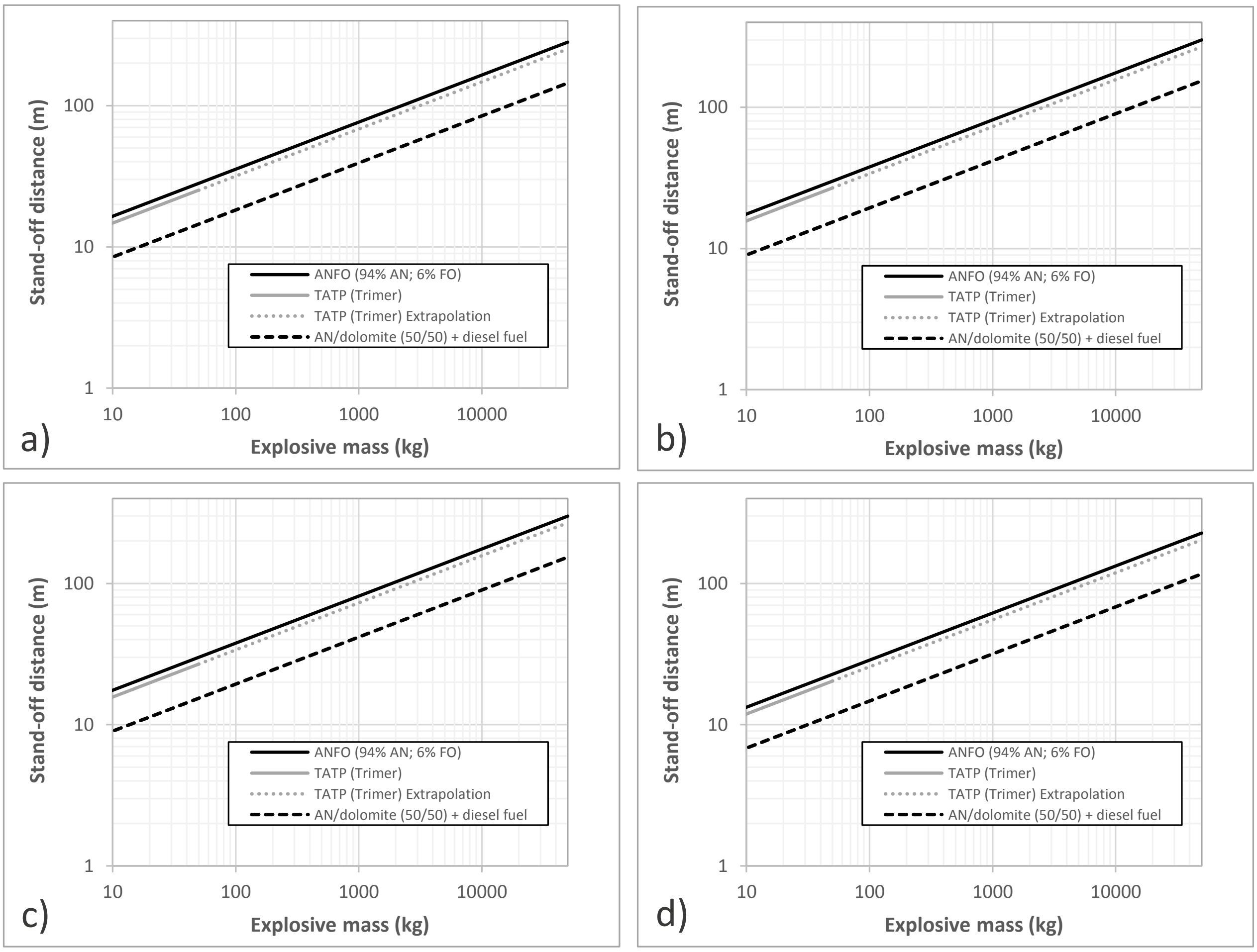

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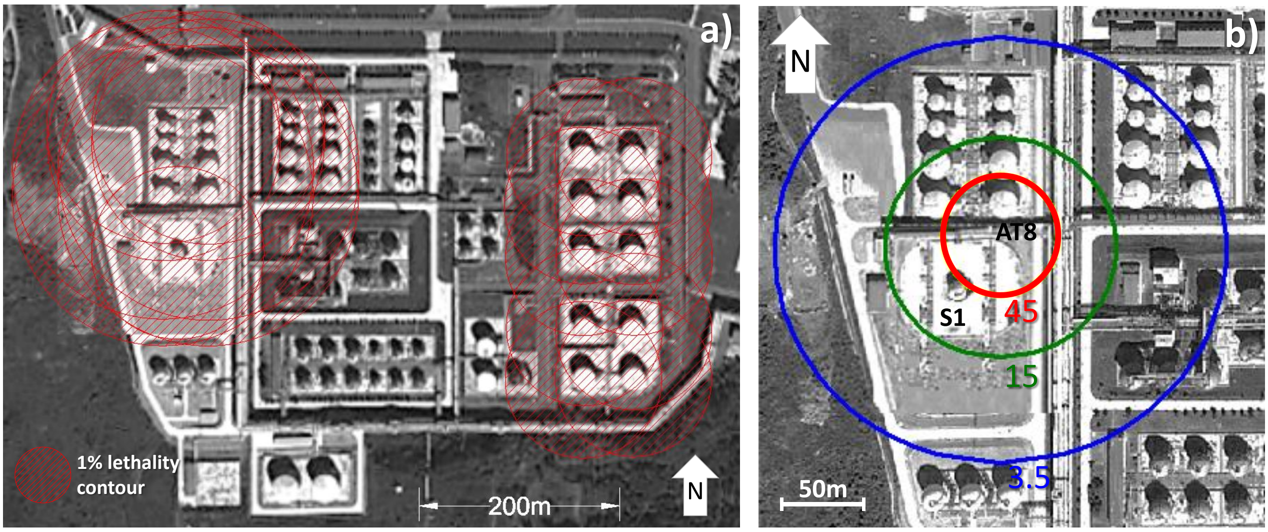

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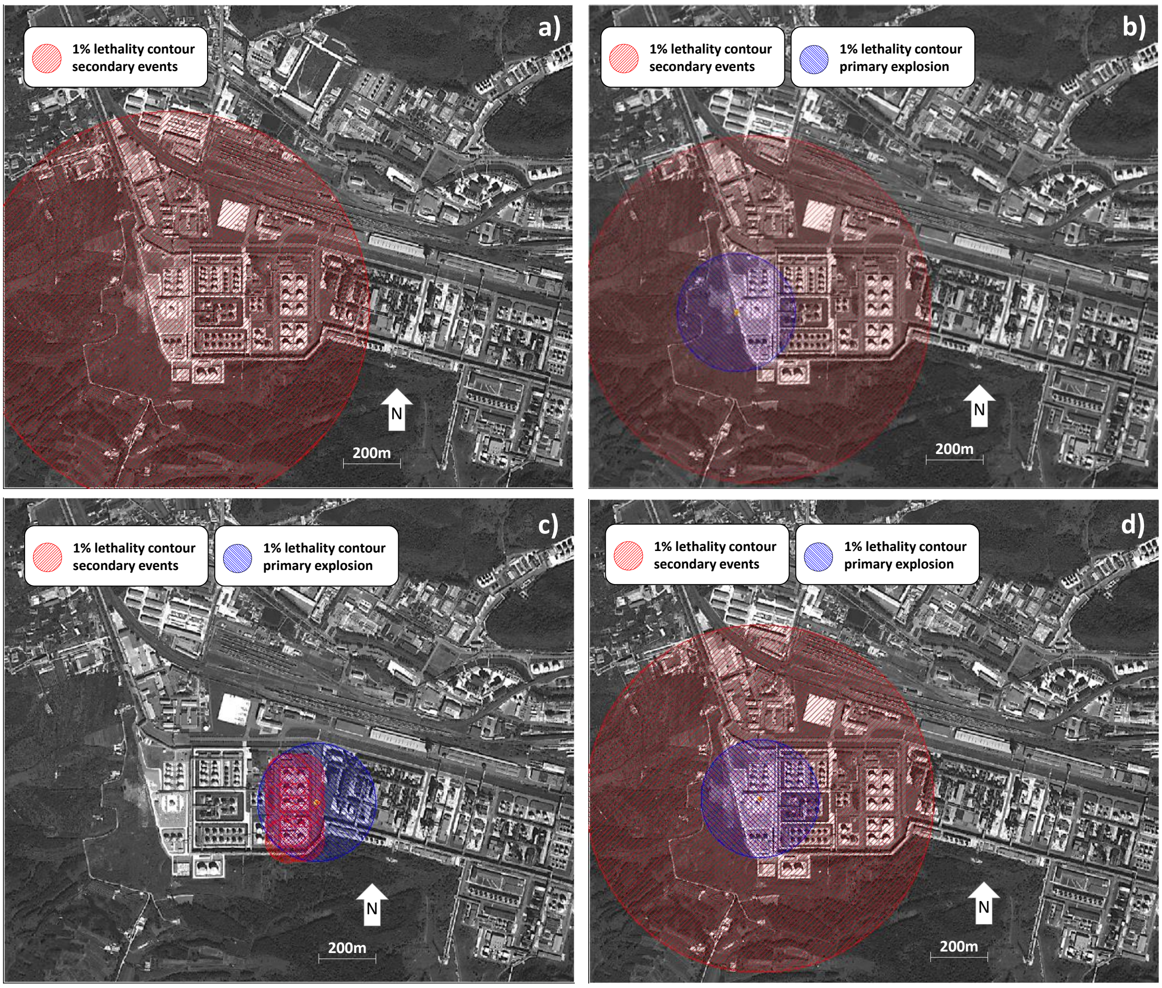

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